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EXPERIMENTAL STUDIES OF LIQUID FILM SUCTION FROM TURBINE STATOR BLADE SURFACE IN WET STEAM FLOW

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ABSTRACT

This paper presents the results of experimental analysis of wet steam flow with liquid film suction process from the surfaces of hollow stator blades. The influence of intrachannel water separation on liquid phase parameters downstream the flat stator blade cascade has been discussed. The investigations were performed at the experimental installation Wet Steam Circuit-1 (WSC). The experiments were performed at initial wetness of the steam y_0 = 6.5% and theoretical exit Mach number M_{1t} = 0.6.

In the studied channel there are 2 suction slots on each blade. They are made at angle 90^o to generatrix of blade profile. Isolated from each other slots are situated on the blade pressure side. The effects of pressure drop in slots on wet steam flow downstream the nozzle blade cascade has been studied. The mass flow rate of liquid phase for each slot has been measured.

Velocity fields of liquid phase downstream the nozzle blade cascade were obtained by the particle image velocimetry (PIV) method.

The results of experimental study allow modifying the operating variables of intrachannel moisture separation systems for steam turbines stages.

NOMENCLATURE

a throat of the cascade
b chord of the blade
C_d droplet velocity
C_d^{nosep} droplet velocity in current point at condition without film suction
C_d^{sep} droplet velocity in current point at condition with film suction
C_s steam velocity
d droplet diameter
d_i average diameter of group of the droplets n_i
$2d_n$ droplet diameter interval
G_0 total mass flow rate of two-phase medium before 3 blades of the cascade through the cross section which length is equal to the length of suction slots on these blades
$G_{h.w}$ mass flow rate of hot water after the ejector
G_{1iq0} liquid total mass flow rate within the flow before 3 blades of the cascade through the cross section the length of which is equal to the length of suction slots on these blades
G_{liq} removed liquid absolute mass flow rate
G_{st} sucked steam absolute mass flow rates
$\bar{l}$ relative length
M_{1t} theoretical exit Mach number
n_i number of droplets with diameter d_i
n_Σ total number of droplets
P_0 total pressure
P_a static pressure downstream cascade
P_{ch} static pressure in the suction chamber
P_{st} static pressure in the slot cross section on the surface of the blade
S length of the line
s coordinate along the line
$\bar{s}$ relative coordinate along the line
T_0 total temperature
t pitch of the cascade

$t_{c.w}$ temperature of cold water at the ejector inlet
$t_{h.w}$ temperature of hot water after the ejector
x coordinate along pitchwise direction
y_0 steam initial wetness
α_0 inlet angle of the flow
α_d droplet exit angle
α_s blade stagger angle
α_1 flow exit angle
δC_d dimensionless droplets velocities variation
π pressure drop in the slot
ν slip coefficient
ψ_2 coefficient of separation
ψ_3 sucked steam relative mass flow rate

INTRODUCTION

The operation conditions of last stages of steam turbines depend to a significant extent on the presence of liquid phase. Occurrence of a dispersed phase in the flow leads to a substantial reduction of efficiency and reliability of stages. Moisture contained in wet steam exists both as a polydisperse droplets flow and water films on the surfaces of interblade channels. According to Deich and Filippov, 1987, the coarse droplets are the main source of material erosion damage. These liquid particles are predominantly formed by means of liquid film breakup in stator blade trailing-edge wake. The reliability and efficiency of steam turbine could be improved by removing the liquid film from the surfaces of the stator blades.

At the moment there are a lot of experimental studies of liquid film removing both in laboratory conditions (Gribin et al. (2010); Filippov and Povarov, 1980; Kiryuhin et al. (1975); Abramov, 1970) and real operating turbines (Hoznedl et al. 2012; Kachuriner et al. (1988); Filippov and Povarov, 1980). In these studies optimal geometry of suction slots and pressure drop in them have been obtained.

But still there is not enough information about the influence of film suction process on the structure of liquid phase downstream the stator blade cascade. The knowledge about distribution of droplets main characteristics (velocity, exit angle etc.) depending on operation conditions of suction slots is very important from point of view of the erosion processes analysis. Development of laser diagnostics methods allows applying them to study the wet steam flows in turbine cascades and to obtain necessary data about the influence of intrachannel separation on droplets characteristics downstream the stator blade cascade.

In this paper PIV (particle image velocimetry) method was used to investigate the influence of intrachannel separation of water film on the flow structure in the flat stator blade cascade.

THE EXPERIMENTAL FACILITY AND INSTRUMENTATION

The investigations were performed at the experimental facility WSC – 1 (Wet Steam Circuit-1) in the turbine laboratory of the Moscow Power Engineering Institute. This experimental plant (see Fig. 1) is used to study flow of superheated, saturated and wet steam in channels of the turbines. The principle flow diagram of WSC – 1 is represented in Fig. 1. Superheated steam from extraction of turbine goes through two wetting stages, which are used to reduce the temperature of steam down to the saturation condition by injecting feedwater. These wetting stages are situated at a distance about 50 m from the receiving tank. It provides the equilibrium state of medium which enters the receiving tank.

After the wetting stages steam goes into the receiving tank of WSC – 1 and passes throw the studied channel, which is installed in a removable work part. After it steam enters a condenser and condensate returns in a power plant cycle. The block of feed water sprayers is used to generate a polydisperse droplet environment in the receiving tank. Average diameter of coarse droplets generated by sprayers equals 20-30 µm. The increasing of steam initial wetness is achieving by inclusion of additional sprayers. Meanwhile the pressure of feed water remains constant. The size distribution function of generated droplets measured by methodology described in Deich and Filippov, 1987 in front of the blades cascade in the working part is shown in Fig. 2. Coarse droplet concentration is approximately uniform in the pitchwise direction.

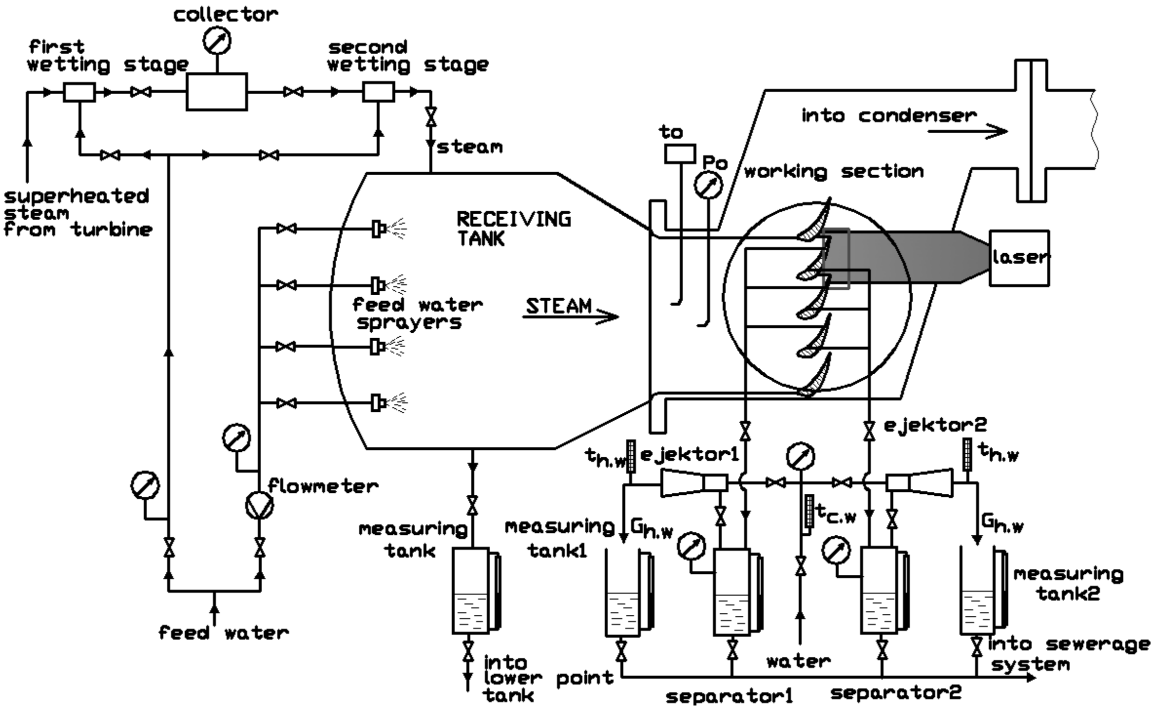

Fig. 1 Schematic diagram of WSC-1

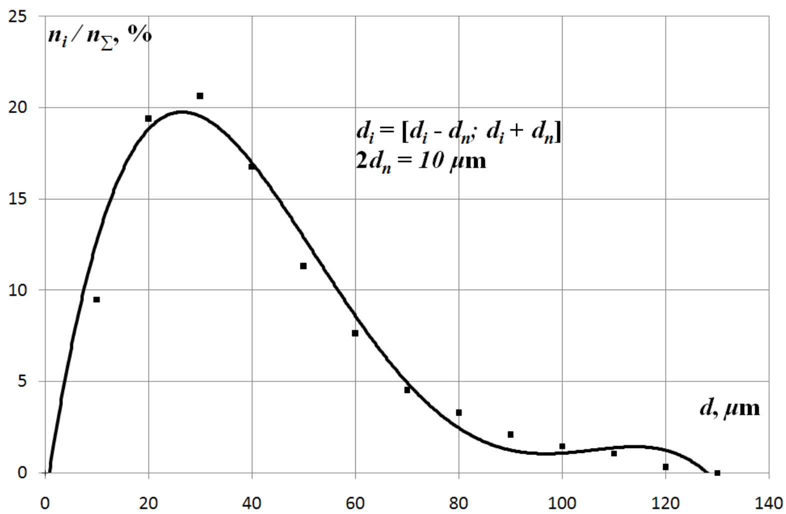

Fig. 2 Size distribution of generated droplets

Total pressure probe and thermal probe were used to measure pressure P_0 and temperature, T_0 at the cascade inlet. The static pressure P_a drains are situated on the shroud plate of cascade at distance 10 mm from the blade trailing edge.

Flat stator blade cascade which consists of 5 blades was studied in the present work. Geometrical features of the investigated cascade are presented in Table 1. A guiding plate is set on the trailing edge of lower blade to reduce the boundary effects as shown in Gribin et al. (2009).

Table 1 Geometrical features of the flat stator blades cascade

b, mm	*a*, mm	*t*, mm	α_0	α_s	α_1
100	20.7	74.3	90°	39.1°	16.2°

This paper studies the process of liquid film suction in two slots that are placed on the pressure side of the blades. Length of each slot – 20 mm and they oriented in spanwise direction. Geometry of the slots and their location on the blade are shown in Fig.3. Two-phase medium, which was sucked through the slot I, enters separator 1 where water is gravitates, while steam is sucked by water-jet ejector 1 (see Fig. 1). Mass flow rate of sucked steam was determined by measuring of mass flow rate of hot water after the ejector $G_{h.w}$, cold water temperature at the ejector inlet $t_{c.w}$ and hot water temperature after the ejector $t_{h.w}$ and solving the equations of mass and energy conservation recently Gribin et al. (2010). The same measurement system is provided for slot II. Static pressure, P_{st} on the blade surface and pressure, P_{ch} in the suction chamber were measured (see Fig. 3) to determine the pressure drop in the slot:

$$\pi = {}^{P_{ch}}\!\big/_{P_{st}} . \qquad (1)$$

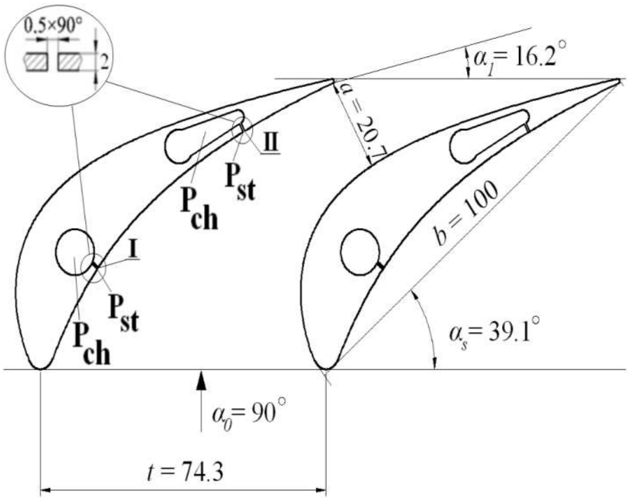

Fig. 3 Blade scheme

In order to study the characteristics of liquid phase downstream the cascade, we used the laser diagnostic system PIV-IT which is presented in Fig. 4. The medium flow downstream of the blade cascade has been illuminated by planar laser knife with thickness 1 mm formed by a dual pulsed laser. The high-speed camera takes 600 series of the illuminated droplets – 2 pictures with size 3760x1800 pixels are taken at 400 ns intervals. The obtained data was processed by means of PIV method which allows to measure of two-component instantaneous droplets velocity fields on a regular mesh (the speed range is 0.001 – 1000 m/s; the error of measurement isn't more than 3.5%).

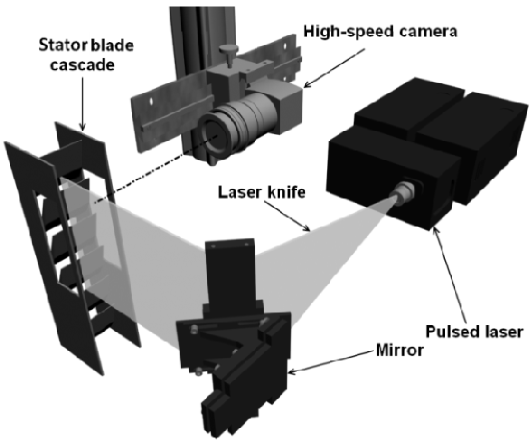

Fig. 4 Laser diagnostics system

INTRACHANNEL SEPARATION MASS FLOW RATES

Experimental studies of the intrachannel separation in flat stator blade cascade were carried out at initial wetness of steam y_0 = 6.5%, inlet total pressure P_0 = 40000 Pa and M_{1t} = 0.6. Suction regimes were defined by parameter π (see formula 1) and investigated in area of π = 0.75-0.97. In such range of values of π effects of steam condensation in drains and separators are negligible due to good thermoinsulation. As a result, the mass flow rates of sucked moisture were obtained.

The value of sucked liquid relative mass flow rate ψ_2 (coefficient of separation) and sucked steam relative mass flow rate ψ_3 were used to estimate the efficiency of separation according to Gribin et al. (2010):

$$\psi_2 = G_{liq} / G_{liq0} , \tag{2}$$

$$\psi_3 = G_{st} / G_0 . \tag{3}$$

Coefficients ψ_2 and ψ_3 depending on π for the slots I, II and combined regimes of intrachannel separation are shown in Fig. 5. For combined regimes coefficient ψ_2 was related to parameter π of the slot II and pressure drop in the slot I was equal π = 0.9.

Mass flow rate of sucked liquid through the slot I is less than through the slot II for all investigated cases. Variation of π does not have considerable influence on mass flow rate of sucked film through the slot I. Because liquid film fully sucks through the slot I according to Khizanashvili, 1973.

With increasing of π the mass flow rate of sucked water through the slot II increases. This is due to the fact that increasing of π (i.e. decreasing of the pressure drop in the slot) leads to transformation of liquid and steam flow structure through the slot. At low values of π steam mass flow rate through the slot is high and it decreases the flow section of the liquid stream. With increasing of π steam mass flow rate decreases (see Fig 5, b) and the flow section of sucked film increases. Thus the maximum mass flow rate of sucked liquid phase is located in the area of π > 0.9.

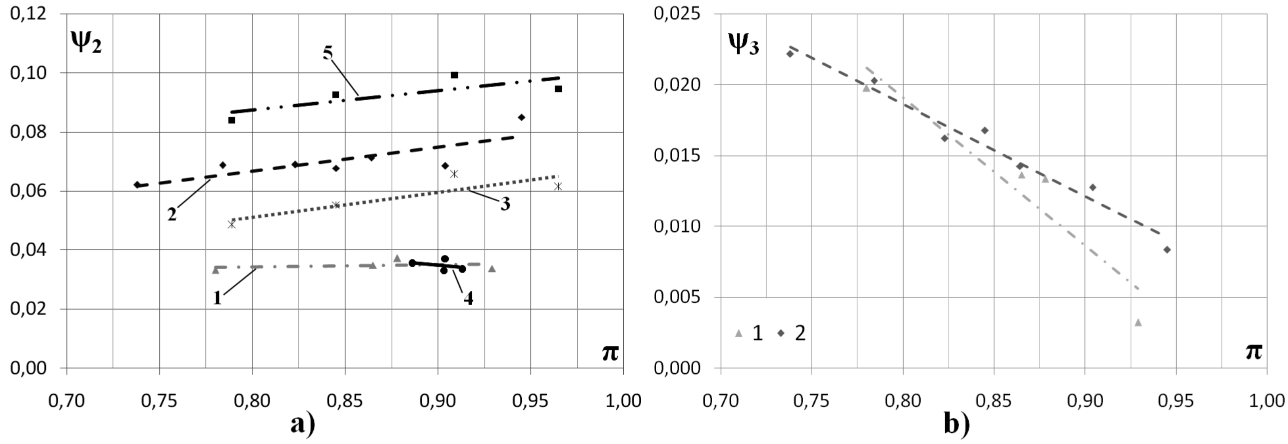

Fig. 5 Relation of coefficient of separation ψ_2 (a) and steam relative mass flow rate ψ_3 (b) to parameter π. 1 – mass flow rate through slot I working alone; 2 – mass flow rate through slot II working alone; 3 – mass flow rate through slot II working in combined regime; 4 – mass flow rate through slot I working in combined regime; 5 – overall mass flow rate through slots working in combined regime

Combined intrachannel separation through the slots I and II has its influence on the mass flow rate of sucked liquid only for the slot II. The slot I fully removes liquid film and the new one, with

lower mass flow rate, generates. It is contradict previously obtained data, where turning on of the upstream slot had influence only at initial wetness $y_0 \leq$ 1-2% Abramov, 1970. Apparently it is depend on the initial dispersion at the inlet of the cascade. In work Abramov, 1970 diameters and concentration of the droplets were enough to form new film with maximum mass flow rate at the sufficiently small distance on the blade surface. However total mass flow rate of sucked moisture through both slots greater than mass flow rate sucked through the slot II working alone. Thus combined intrachannel separation through the two slots located on the pressure side of the stator blade working in area $\pi > 0.9$ allows removing maximum amount of liquid from the channel.

APPLICATION OF THE PIV METHOD

Liquid phase characteristics downstream the stator blade cascade

The cross-correlation method PIV was used to obtain the velocity characteristics of liquid phase downstream the stator blade cascade.

Average velocity vector field of liquid phase downstream the blade cascade at condition without intrachannel moisture separation is presented in Fig.6. Contours of the droplets average velocity are also shown. Obtained droplets vector fields were processed by the additional post-processing method, based on work Garcia, 2010, in order to minimize the negative effects, connected with the presence of liquid phase in the flow (formation of liquid film on optic glasses, laser beam interference phenomena, flashes, formed by illumination of large droplets).

Two droplets streams in which liquid phase velocity less than in the flow core are clearly seen on presented vector field. The first one is a “wake” located zone on the side of the blade`s suction surface (area 1 in Fig. 6) and the second one is a zone in the blade trailing-edge wake (area 2 in Fig.6). Droplets in stream 1 move with considerably high angles in direction from blade trailing edge to flow core.

The distributions of the liquid phase parameters in pitchwise direction along the line 0,1*b* (see Fig. 6) are shown in Fig. 7. Here:

$$\bar{l} = \frac{x}{t}. \qquad (4)$$

Two minimums take place on the velocity profile. They correspond to the droplets streams noted earlier. It is important to note that the value of droplets velocities in considered zones are on the same level. From the Fig. 7 we can see that angles distribution has one peak, which corresponds to stream 1. In stream 2 (in trailing-edge wake) droplets angles increase in pitchwise direction from flow core to stream 1 and there is no extremum in this zone. The maximum value of droplets exit angle equals 34 degrees. Such character of droplets movement indicates that stream of liquid particles in zone 1 (see Fig 6) is formed by liquid phase at blade cascade inlet. These droplets pass the channel without interaction with its walls and cross the trailing-edge wake in direction from pressure side to suction side of the blade. Also these droplets may occur at liquid film flow around curved surface of trailing edge. Question about the process of liquid particles formation in this zone should be studied in grater detail.

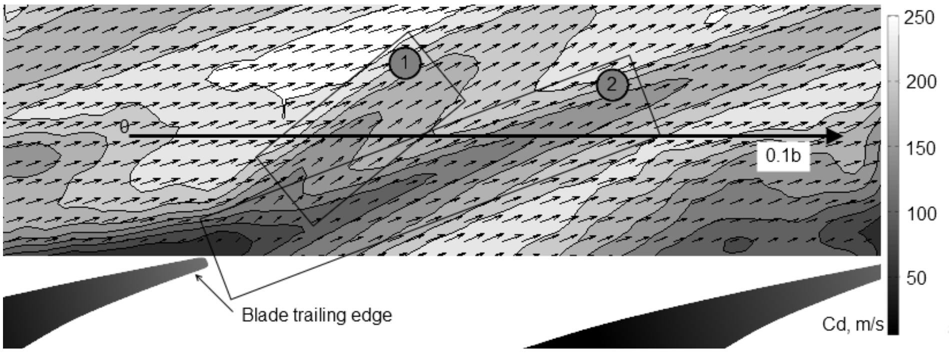

Fig. 6 Liquid phase vector field and distribution of velocities

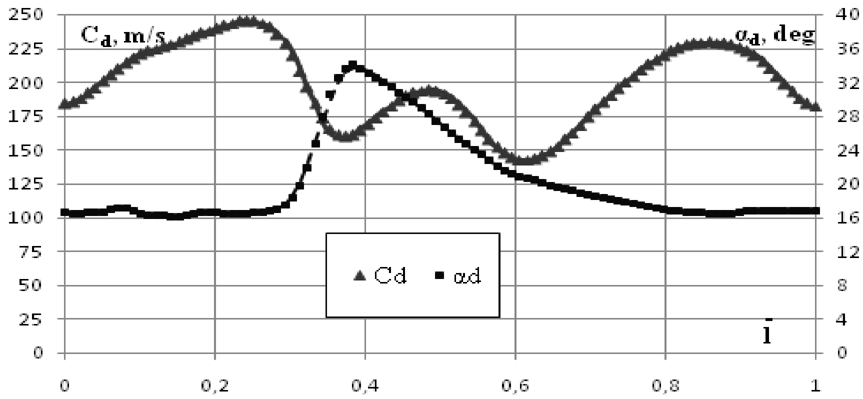

Fig. 7 Distribution of droplets velocity and angle in pitchwise direction

In order to analyze the influence of intrachannel moisture separation parameters on the coarse droplets characteristics downstream the blade cascade the additional filtering criterion was used. It considered that the droplets with the slip coefficient *ν* that does not exceed 0.8 are regarded to be a coarse ones and erosion-hazardous recently Filippov et al., 2012. The value of *ν* is calculated as:

$$\nu = \frac{C_d}{C_s}. \qquad (5)$$

In order to estimate the value of slip coefficient and to reject the vectors of fine liquid particles (with slip coefficient greater than 0.8) the Ansys Fluent CFD code, described in the work Filippov et al., 2014, was used to obtain the steam phase parameters. We used the standard k-ε turbulence model, which was modified in accordance with Avetisyan et al, 2007, due to which it became suitable for calculating the wet steam flows. In addition, the thermodynamic properties of water and steam incorporated into the wet steam model implemented in the Ansys Fluent CFD code were replaced by the formulations presented by the International Association for the properties of Water and Steam recently Wagner and Pruß, 2002. This was done with the aim of the more accurately calculating certain condition parameters and comparing them with the results of the experimental measurements.

Fig. 8 represents the area downstream the stator blade cascade, where coarse droplets were identified by PIV method. So, a brief analyze of liquid phase motion has shown that erosion-hazardous droplets are distributed in two typical areas:

1. Blade trailing edge wake. Here droplets are formed by the breakup of liquid film from trailing edge. As shown in Deich and Filippov, 1987, this zone is the main source of erosion-hazardous liquid particles.

2. Area downstream the stator blade cascade where probably move droplets, which pass the channel without interaction with its walls and cross the trailing edge wake. This stream of liquid particles can`t be controlled by intrachannel separation systems.

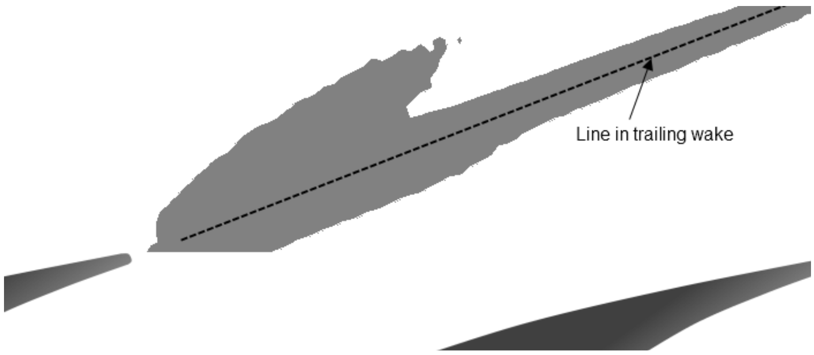

Fig. 8 Area of coarse droplets expansion downstream the blade cascade

Conditions with intrachannel separation from slots have been analyzed by the same way. Results of PIV method implementation has shown that pressure drop on slots does not contribute the variation of liquid phase parameters downstream the blade cascade. Fig. 9 represents the distribution of dimensionless droplets velocities variation with respect to condition without film suction alone the line in blade trailing-edge wake (see Fig. 8). Here:

$$\delta C_d = \frac{\left| C_d^{sep} - C_d^{nosep} \right|}{C_d^{nosep}}, \tag{6}$$

$$\bar{s} = \frac{s}{S} \ . \tag{7}$$

The maximum change of velocity value doesn't exceed 3,5%, which is at level of measurement error. Thus the lack of effect of slots pressure drop on the droplets velocity characteristics downstream the blade cascade indicates that the character of liquid film flow near the blade trailing edge doesn`t change. It can be explained by the following way: after the film sucked in the slot, liquid film is formed again due to the deposition of droplets on a blade surface and near the trailing edge it`s mass flow rate achieves critical values (see Khizanashvili, 1973).

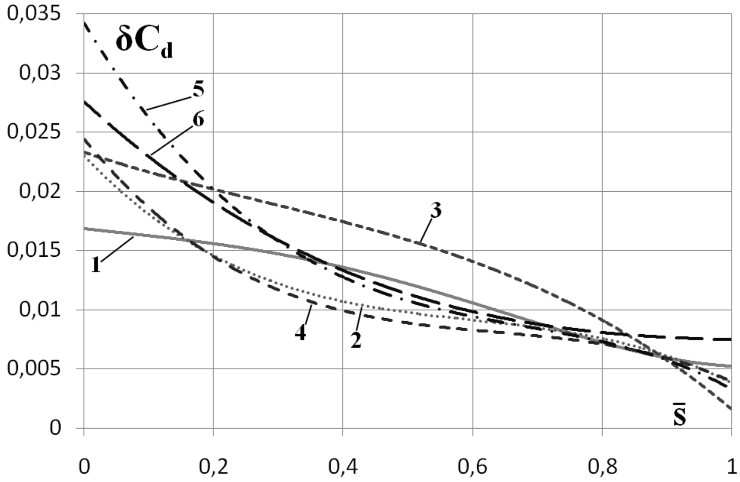

Fig. 9 Distribution of dimensionless droplets velocities variation with respect to condition without film suction. 1 – π_I = 0.78; 2 – π_I = 0.93; 3 – π_{II} = 0.78; 4 – π_{II} = 0.86; 5 – π_I = 0.9, π_{II} = 0.95; 6 – π_I = 0.82, π_{II} = 0.88

Visualization of the droplet flow downstream of the blade cascade

In addition to analyzing the droplets flow characteristics, the laser diagnostics system provides visualization of the discrete-phase flow pattern. Fig. 10 shows typical photos for condition without suction and condition with suction. There are two specific droplets streams downstream the stator blade cascade in these pictures:

1. Fog of fine droplets which move without slip relative to steam flow.
2. Separately observed droplets. They are in the most cases correspond to coarse droplets.

One of the droplets source downstream the blade is disruption of the water film from the trailing edge. As a result, a "tongue" of liquid is formed near the trailing edge. It is destroyed by clusters of droplets and coarse droplets by the steam flow (see Fig. 10, 1, 3) at condition without moisture suction. The analysis of a series of images has shown that the formation of droplets downstream the trailing edge is unsteady. The change of the droplets flow structure is clearly seen by comparison of photos in Fig. 10-2 and 10-4, where the variation of coarse droplets concentration is observed.

At the condition with moisture suction, "tongues" of liquid downstream the blade trailing edge appears too but they are smaller than at the condition without intrachannel separation. It is validating the conclusion, made above, that liquid film forms again on the blade’s surface downstream the slots but with lower film thickness. Also clusters of droplets are not generated at the condition with film suction (see Fig. 10, a, b, c, d).

Visual comparison of photos allows drawing a conclusion: concentration of coarse droplets decreases at conditions with intrachannel water separation.

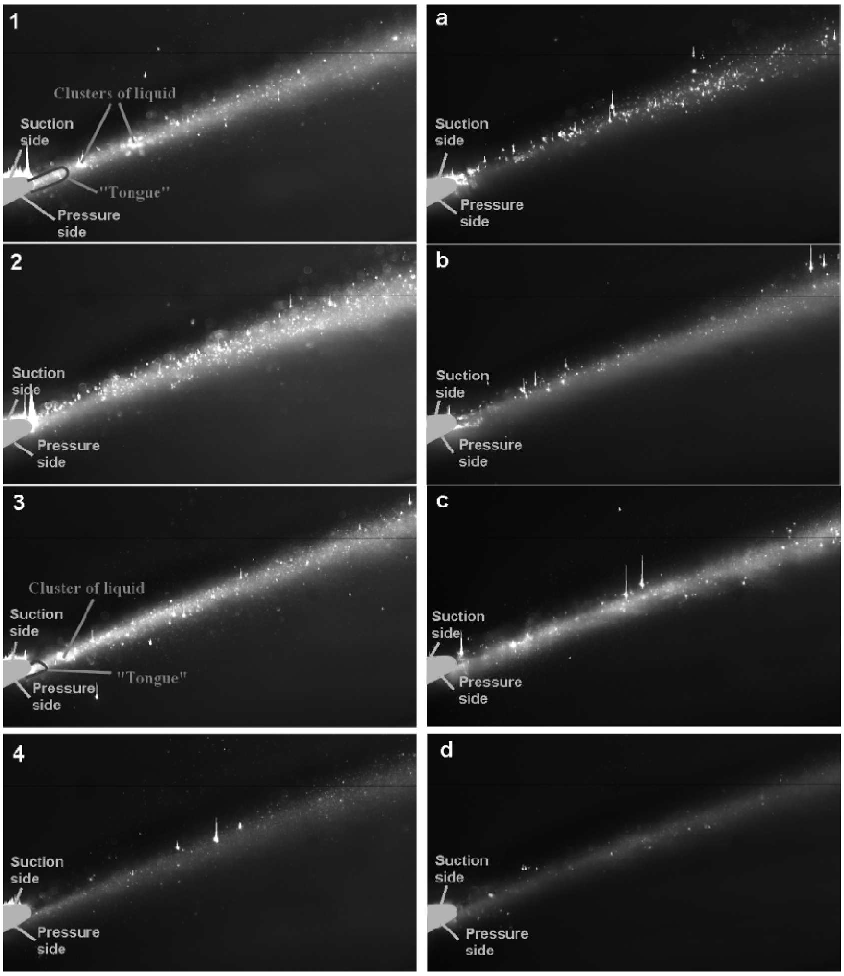

Fig. 10 The structure of the liquid flow downstream of the blade at condition without intrachannel separation (1-4) and with intrachannel separation π_I = 0.9, π_{II} = 0.95 (a-d)

CONCLUSIONS

An analysis of obtained experimental data allows making the following conclusions:

1. Mass flow rate of sucked through the slot I moisture significantly less, then through the slot II, and does not change with change of pressure drop in the slot. This effect is connected with the mechanisms of formation and flowing of liquid film in the stator blade channel.
2. Mass flow rate of removed through the slot II liquid grows with increasing of π parameter. The most effective are regimes with $\pi > 0.9$.
3. Combined intrachannel separation through the slots I and II appears to be the most effective and allows to remove maximum of moisture from the flow.
4. Analyze of the liquid phase motion has shown that the erosion-hazardous droplets are distributed in two typical areas: blade trailing-edge wake, and the area downstream the stator blade cascade from the side of blade suction surface.
5. Intrachannel separation does not provide considerable influence on velocities of droplets downstream the blade cascade at certain experimental conditions.
6. Visual analysis of the droplets streams photos has shown that concentration of coarse droplets decreases at conditions with suction of liquid film.

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